Innovative cropping systems to reduce N inputs and maintain wheat yields by inserting grain legumes and cover crops in southwestern France

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Abbreviations

NAR, apparent nitrogen recovery efficiency; NHI, nitrogen harvest index; NUE_y, nitrogen use efficiency for yield; WUE_{b-C}, rotation water use efficiency for production of aboveground biomass C; WUE_{y-C}, rotation water use efficiency for production of grain C; WUE_y, water use efficiency for yield.

Abstract

The reduction in crop diversity and specialization of cereal-based cropping systems have led to high dependence on synthetic nitrogen (N) fertilizer in many areas of the globe. This has exacerbated environmental degradation due to the uncoupling of carbon (C) and N cycles in agroecosystems. In this experiment, we assessed impacts of introducing grain legumes and cover crops to innovative cropping systems to reduce N fertilizer application while maintaining wheat yields and grain quality. Six cropping systems resulting from the combination of three 3-year rotations with 0, 1 and 2 grain legumes (GL0, GL1 and GL2, respectively) with (CC) or without (BF, bare fallow) cover crops were compared during six cropping seasons. Durum wheat was included as a common high-value cash crop in all the cropping systems to evaluate the carryover effects of rotation. For each cropping system, the water use efficiency for producing C in aerial biomass and yield were quantified at the crop and rotation scales. Several diagnostic indicators were analyzed for durum wheat, such as (i) grain yield and 1000-grain weight; (ii) aboveground biomass, grain N content and grain protein concentration; (iii) water- and N-use efficiencies for yield; and (iv) N harvest index. Compared to the GL0-BF cropping system, which is most similar to that traditionally used in southwestern France, N fertilizer application decreased by 58%, 49%, 61% and 56% for the GL1-BF, GL1-CC, GL2-BF and GL2-CC cropping systems, respectively. However, the cropping systems without grain legumes (GL0-BF and GL0-CC) had the highest water use efficiency for producing C in aerial biomass and yield. The insertion of cover crops in the cropping systems did not change wheat grain yield, N uptake, or grain protein concentration compared to those of without cover crops, demonstrating a satisfactory adaptation of the entire cropping system to the use of cover crops. Winter pea as a preceding crop for durum wheat increased wheat grain production by 8% (383 kg ha^{-1}) compared to that with sunflower

– the traditional preceding crop – with a mean reduction in fertilizer application of 40-49 kg N ha^{-1} during the six-year experiment. No differences in protein concentration of wheat grain were observed among preceding crops. Our experiment demonstrates that under temperate submediterranean conditions, properly designed cropping systems that simultaneously insert grain legumes and cover crops reduce N requirements and show similar wheat yield and grain quality attributes as those that are cereal-based.

Keywords

crop diversification, mineral N fertilization, sorghum, soybean, sunflower, pea

1. Introduction

It is estimated that the global population will reach nearly nine billion by 2050, a prospect that poses the challenge of producing food sustainably around the globe given the current scenario of severe environmental degradation and climate change (Pretly et al. 2010). As a consequence, the design of modern cropping systems must focus on the best agronomic, environmental and socio-economic performances. Agricultural systemas have become specialized in many areas of the world, leading to a decrease in crop diversity (FAO, 2011). In Europe, the percentage of arable area cropped with legumes has declined from 4.7% in 1961 to 1.8% in 2011 (Bues et al. 2013). This reduction is explained by the high yield potential of cereals in temperate regions of Europe, the impact of the European Common Agricultural Policy reforms and agronomic difficulties of growing legumes (e.g. low yields and low yield stability, weed competition, disease resistance and grain loss due to lodging and pod dehiscence) (Bues et al. 2013; Preissel et al. 2015). Agronomic research must obtain knowledge about suitable agroecosystems with higher crop diversity that can profit from the broad range of technological tools that are currently available (Tanaka et al. 2002). Increased diversity in cropping systems not only results in lower risks of weeds, pests and diseases, but can also increase a farms'economic resilience to market fluctuations (Ratnadass et al. 2012; Pacín and Oesterheld, 2014).

Nitrogen (N), as one of the most limiting nutrients in agriculture, is a key component in the proper functioning of cropping systems. The availability of relatively inexpensive synthetic N fertilizer in recent decades has led to the decoupling of the N cycle in agroecosystems (Galloway et al. 2003; Tonitto et al. 2006). The specialization of cropping systems in cereal production has exacerbated the dependence on synthetic N fertilizers. This pattern has been worsened by an increase in the share of animal products in the human diet, which has reduced the consumption of plant protein (Lassaletta et al. 2014). The mismanagement of N fertilizer to produce grain in cereal-based cropping systems has adverse environmental consequences, such as nitrate pollution of groundwater, atmospheric pollution from ammonia, and contribution to global warming due to nitrous oxide emissions (Bouwman et al., 2013).

The most common strategy to reduce N fertilizer requirements in cropping systems is the inclusion of legume crops in the rotations (Peoples et al. 2009), whether as a cash or a cover crop. Legumes do not require N fertilizer application because they establish symbiosis with native or inoculated soil bacteria to fix atmospheric N_2. Given the low C:N ratio of their crop residues, they leave higher amounts of N available for subsequent crops due to lower N immobilization during their decomposition (e.g. Justes et al. 2009) and, in some cases, they can also accelerate the decomposition of native soil organic matter (Kuzyakov, 2010). Once legumes are included in a rotation, the key objective is to reach synchrony with the N requirements of the subsequent crop (Stute and Posner, 1995; Hauggaard-Nielsen et al. 2009). Because of this, the cropping system must be completely adapted, beyond the inclusion of legume crops. As demonstrated by Gan et al. (2003), arranging crops in an appropriate sequence leads to more efficient use of resources, which improves soil productivity at the system level. In turn, the crop sequence must be accompanied by the best crop-management practices (e.g. N fertilization rates and timing, soil management, weeding, irrigation).

Unfortunately, cropping systems are not always completely adapted in practice. For instance, Preissel et al. (2015) claimed that some farmers do not significantly reduce N fertilizer application after a legume crop. Hauggaard-Nielsen et al. (2003) and Plaza-Bonilla et al. (2015) stressed the greater risks of nitrate leaching after grain legumes, which results in the need to include cover crops, a practice not usually considered on commercial farms.

Previous studies mainly focused on the influence of legume presence or absence on one performance factor of the subsequent crop, which seems insufficient for a complete analysis of effects of grain legumes in cropping systems. The objective of our study was to evaluate impacts of introducing grain legumes and cover crops in completely redesigned cropping systems (i.e. adapting all management practices) on wheat yield and grain quality to reduce N fertilizer and irrigation dependence. We focused on durum wheat as an indicator of the carryover effects of the cropping system.

2. Materials and Methods

2.1. Experimental site and treatment design

A field experiment was established in 2003 at the Auzeville station of the Institut National de la Recherche Agronomique (southwestern France, 43º 31’N, 1º 30’ E, 150 m.a.s.l.). Over the last three decades, mean annual rainfall was 685 mm, air temperature was 13.7ºC and potential evapotranspiration was 905 mm. At the beginning of the experiment, in the upper 30 cm of soil, soil texture was clay loam and mean (±1 standard deviation) pH (H_2O, 1:2.5) was 7.0±0.5, CEC was 18.1±3.6 cmol+ kg^{-1}, organic C was 8.7±1.0 g kg^{-1} and organic N was 1.1±0.1 g kg^{-1}. Six cropping systems resulting from the combination of three 3-year rotations with 0, 1 and 2 grain legumes (GL0, GL1 and GL2, respectively) with (CC) or without (BF, bare fallow) cover crops were compared (Fig. 1). Cover crops differed among cropping systems to reduce susceptibility to nitrate leaching and increase N availability for the subsequent cash crop (Fig. 1). Durum wheat, a traditional cereal in this region, was established in the six cropping systems since it is a high-value cash crop and is sold for semolina and pasta production. Durum wheat acted as an indicator of each system’s performance since it was present each year in all rotations, which enabled evaluating the carryover effects of rotation. Within each 3-year rotation, each crop was grown every year to account for interannual climatic variability. The experiment was replicated in two contiguous blocks to include variability in soil texture. Regarding to this, sand and clay proportion was 32±5% and 28±4% for block 1 and 40±5% and 28±4% for block 2. Consequently, 36 plots were cropped (6 rotations × 3 crops × 2 replicates). Plot size was 87.5 × 15 m.

2.2. Crop management

N fertilization was adapted each year for each cash crop according to the balance-sheet method (e.g. Meynard et al. 1997), which considered the N requirements of the cash crop, the availability of soil N and N mineralization estimated using a predicted mineral N balance. Ammonium nitrate fertilizer was divided into two or three applications at the stages of beginning of stem elongation, two nodes and heading of durum wheat, while urea was applied once during the first week after sowing of sorghum and sunflower, just before mechanical weeding (Table 1).

Soil was conventionally tilled to reduce herbicide dependence. One pass of a rotary harrow followed by a cultipacker was performed before sowing. Moldboard plowing was also performed to avoid weed competition and reduce soil compaction, but only during autumn before spring-sown crops, while mechanical weeding between rows was used in sorghum and sunflower crops. All crop residues were chopped and incorporated into the soil; only grain was exported. Finally, cover crops were terminated with a disk plow to avoid the use of broad-spectrum herbicides. Pesticide application to cash crops was minimized as much as possible, using products that local farmers typically applied. Narrow-row crops (i.e. durum wheat, peas, cover crops) were sown at a depth of 2-4 cm with a conventional seeding machine, while a precision air seeder was used for wide-row (i.e. 45 cm) crops (i.e. soybean, sunflower, sorghum).

In case of water deficit, crops were irrigated to 70-80% of the potential evapotranspiration to efficiently use irrigation water, which is limited and expensive in the area. Irrigation rates were calculated for each crop using AqYield, a simple dynamic crop model that predicts daily water availability in the soil and crop actual transpiration (Constantin et al. 2015). Irrigation water was applied with a large-volume sprinkler and to facilitate the establishment of cover crops (Table 2).

Grain was harvested with a commercial harvesting machine. Soil water and mineral N contents were measured at three key dates to calculate and adjust the water and N balances. Weather variables (e.g. air temperature, precipitation) were recorded at the experimental site using an automated station.

2.3. Soil and crop sampling and analysis

In each of the plots, a 18 × 15 m sampling area was established to overcome the effect of spatial variability. Within the sampling areas, a non-fertilized 9 × 12 m control was established for fertilized crops. In each season, soil water and mineral N contents in the entire soil profile (i.e. 0-120 cm deep) were quantified at four depth intervals (0-30, 30-60, 60-90 and 90-120 cm) at three key dates: the beginning and end of winter and just after harvest. To do so, a composite sample of ten sub-samples was obtained for each sampling area and depth. Soil moisture was determined gravimetrically, and soil mineral N was quantified with a continuous flow autoanalyzer (Skalar 5100, Skalar Analytic, Erkelenz, Germany).

Crop aerial biomass was measured at harvest by cutting 1 m^2 of plants at the soil surface in the two sampling areas and in the non-fertilized control. The samples were air-dried at 80ºC for 48 h, weighed and the grain threshed, counted and weighed. C and N concentrations of the biomass and grain were determined by dry combustion with a LECO-2000 analyzer (LECO, St. Joseph, MI, USA). Durum wheat grain protein concentration was calculated by multiplying the grain N concentration by 5.7.

2.4. Calculations and data analysis

2.4.1. *Water use efficiency of entire rotation cycles*

The water use efficiency for producing aerial biomass C ($WUE_{b\text{-}C}$) in a rotation cycle (i.e. three growing seasons) was calculated as:

where Aerial $biomass_{rot}$ is the amount of aerial biomass of the three cash crops in a rotation cycle, and 0.45 is proportion of aerial biomass that is C (taken from measurements).

WU_{rot} is water use during a rotation cycle, calculated as:

$$WU_{rot} = (SWC_i - SWC_f) + Precipitation_{rot} + Irrigation_{rot} - Drainage_{rot}$$

where SWC_i and SWC_f are soil water contents of the entire soil profile (0-120 cm) at the beginning and end of a rotation cycle, respectively; $Precipitation_{rot}$ is the amount of water received as rainfall or snow during a rotation cycle; $Irrigation_{rot}$ is the amount of irrigation water applied during a rotation cycle; and $Drainage_{rot}$ is the amount of water lost as drainage below the rooting depth (120 cm) during a rotation cycle predicted by the STICS model. Information about calibrating and validating the STICS model and predicting water drainage for this experiment is given by Plaza-Bonilla et al. (2015).

The water use efficiency for producing grain C ($WUE_{y\text{-}C}$) in a rotation cycle was calculated as:

where Grain $biomass_{rot}$ is the amount of grain produced during a rotation cycle, and 0.45 is the proportion of grain biomass that is C (taken from the mean of measurements).

2.4.2. *Water and N efficiency indexes for durum wheat*

The water use efficiency for durum wheat yield (WUE_y) was calculated as:

where WU is the water use of durum wheat, calculated as:

$$WU = (SWC_{sow} - SWC_{harv}) + Precipitation + Irrigation - Drainage$$

where SWC_{sow} and SWC_{harv} are the soil water contents of the entire soil profile (0-120 cm) at the sowing and harvest of durum wheat, respectively; Precipitation is the amount of water received during the durum wheat cycle; Irrigation is the irrigation water applied to durum wheat (only in 2009); and Drainage is the amount of water lost as drainage below the rooting depth (120 cm) during the durum wheat cropping period (i.e. from sowing to harvest) predicted by STICS (see details in Plaza-Bonilla et al., 2015).

The apparent N recovery efficiency (NAR) was calculated as:

where N acquired is the amount of N in the biomass of the fertilized crop (adding a proportion of 15% for root biomass and rhizodeposits), and N $acquired_{0N}$ is the amount of N in the biomass of the non-fertilized (N0) control (also adding 15% for root biomass).

The N harvest index of durum wheat (NHI) was calculated as:

where N grain is the amount of N in the grain of durum wheat.

The N use efficiency of the durum wheat yield (NUE_y) was calculated as:

where NU is the N uptake or acquired by durum wheat, calculated as:

$$NU = (SMN_{sow} - SMN_{harv}) + N\ fertilization + N\ irrigation - N\ leaching + N\ mineralized$$

where SMN_{sow} and SMN_{harv} are the soil mineral N contents of the entire soil profile (0-120 cm) at durum wheat sowing and harvest, respectively; N fertilization is the amount of N fertilizer applied to durum wheat; N irrigation is the amount of N added with irrigation water at a concentration of 0.004 g N L^{-1}; N leaching is the nitrate-N leached below a depth of 120 cm predicted by STICS (Plaza-Bonilla et al. 2015); and N mineralized is the amount of net N mineralized from the soil and avalaible for the crop uptake during the durum wheat cropping period, calculated as:

$$N\ mineralized = N\ acquired - SMN_{sow} + SMN_{harv} + N\ leaching - N\ fertilisation - N\ irrigation$$

2.4.3. Statistical analysis

Statistical analyses were performed for the entire experimental period between the establishment of the cover crops in 2004 (i.e. July to October 2004) and the harvest of the cash crops in 2010 (i.e. July to October 2010). Analyses of variance were performed using the JMP 11 Pro statistical package (SAS Institute Inc, 2014) for a completely randomized design when the effects of cropping systems were analyzed, and for a split-plot design when the effects of the preceding crop (main plot, equivalent to GL) and CC (sub-plot) were analyzed. Normality was tested with the W test of Shapiro-Wilk. When needed, a log-transformation was used to normalize data and its variances. When the assumption of normality was not met, the nonparametric Kruskal-Wallis test was used. Significant differences among treatments were identified at the 0.05 probability level of significance.

3. Results

3.1. Environmental conditions during the experiment

Total rainfall from July to June of the six seasons (2004-2005 to 2009-2010) was 502, 530, 571, 570, 770 and 663 mm, respectively. Monthly rainfall had high variability between and within years, as is characteristic for the region's climate. With lower variability among years than rainfall, mean monthly air temperature ranged between 2.9 and 25.2ºC in December 2005 and July 2006, respectively (Fig. 2).

3.2. Performance of the cropping systems compared

In the three cropping systems without cover crops, the insertion of one (GL1-BF) and two (GL2-BF) grain legumes led to a 28% and 30% reduction, respectively, in the N fertilizer applied to durum wheat compared to that for GL0-BF. For the cropping systems with cover crops, the reduction was 8% and 18% for GL1-CC and GL2-CC, respectively, compared to GL0-CC. The use of cover crops in the GL0 system (i.e. GL0-CC vs. GL0-BF) led to a slight decrease (-5%) in the amount of N fertilizer applied to durum wheat. As a difference, the insertion of cover crops in the GL1 and GL2 systems was accompanied by a 21% and 11% increase, respectively, in durum wheat N fertilizer (Table 1).

Averaging the two three-year rotation cycles studied (i.e. 2005-2007 and 2008-2010), the GL0-BF cropping system had higher mean $WUE_{b\text{-}C}$ than the other cropping systems, except for GL0-CC. The insertion of grain legumes in the cropping systems reduced the $WUE_{b\text{-}C}$ of the BF and CC treatments (Table 3). Similarly, $WUE_{y\text{-}C}$ was higher in the GL0-BF and GL0-CC cropping systems than in those with grain legumes. Interestingly, cropping systems with cover crops did not differ in $WUE_{y\text{-}C}$ or $WUE_{b\text{-}C}$ from systems without cover crops (i.e. BF). The rotation cycle had a significant effect on $WUE_{b\text{-}C}$ and $WUE_{y\text{-}C}$, which indicates that climatic conditions also influenced WUE; the values in the 2008-2010 cycle were lower than those in 2005-2007.

The cropping systems significantly influenced soil water and mineral N contents in mid-November, before the beginning of the usual drainage period in these soil and climate conditions (i.e. before sowing winter crops) (Table 4). No differences were observed between cropping systems in soil water content at the soil surface (depth of 0-30 cm). The GL2-BF system had higher soil water content at 30-60 cm depth than GL1-CC and at 60-90 cm depth than GL1-BF and GL1-CC. At the deepest soil depth studied (i.e. 90-120 cm), GL2-CC had higher soil water content than the other cropping systems, except for GL2-BF (Fig. 3a). GL1-BF and GL2-BF had higher soil mineral N content in mid-November than the cover crop treatments (GL0-CC, GL1-CC and GL2-CC) in most of the depth intervals, with intermediate values for GL0-BF at depths of 0-30 and 30-60 cm (Fig. 3c).

3.3. *Preceding crop effects on durum wheat*

The preceding crop did not significantly influence durum wheat N uptake (P = 0.063). However, a trend of higher values was observed when winter pea was the preceding crop compared to sunflower (216 vs. 197 kg N ha^{-1}), with spring pea showing intermediate values (Table 5). As expected, the cover crop treatments and their interaction with the preceding crop did not significantly influence N uptake by durum wheat, since N fertilization was adjusted with the balance-sheet method. As a consequence, the most relevant indicator is the amount of N fertilizer applied to wheat depending on each preceding crop. No significant effects from the preceding crop or cover crops were observed on durum wheat NAR or NHI (Table 5).

The mean durum wheat grain yield over the six cropping seasons was 5377 kg ha^{-1} with winter pea as the preceding crop, 5137 kg ha^{-1} with spring pea, and 4993 kg ha^{-1} with sunflower, with no significant differences between them (Table 6). The stability of durum wheat grain yield over time was similar among preceding crops; the coefficient of variation was 15.7%, 14.7% and 18.3% with sunflower, winter pea and spring pea as preceding crops, respectively (data not shown). Durum wheat grain N content was similar with winter or spring pea as preceding crops compared to sunflower, despite lower N fertilizer applications to wheat. However, wheat N uptake in 2006 was higher after winter pea than after sunflower or spring pea. Incorporation of mustard as a cover crop in the period between winter or spring pea and wheat slightly reduced ($p = 0.023$) wheat N uptake when compared to their counterparts under bare fallow (6 and 8 kg N ha^{-1} for winter and spring pea, respectively). Conversely, the inclusion of vetch between sunflower and wheat did not influence the N uptake of the latter. The preceding crop significantly influenced the 1000-grain weight of wheat, with higher values for sunflower as the preceding crop in 2005 and winter pea as the preceding crop in 2009. Conversely, preceding crops did not influence protein concentration in durum wheat grain (Table 6). The use of cover crops did not affect wheat's 1000-grain weight or grain protein concentration. The year had a significant influence on the performance of durum wheat, with mean grain yields ranging from 3949 in 2009 to 5872 kg ha^{-1} in 2010 among the cropping systems. However, the lowest grain production in 2009 had the highest grain protein concentration (Table 6).

The preceding crop generally did not affect mean durum wheat WUE_y of the six cropping seasons. However, in 2006, winter pea as a preceding crop led to higher WUE_y than sunflower, with intermediate values for spring pea (Table 7). A significant interaction was observed between the preceding crop and year for wheat NUE_y. Winter and spring peas as preceding crops led to higher wheat NUE_y than sunflower in 2006 and 2008, while sunflower as a preceding crop led to higher wheat NUE_y than spring pea in 2007 (Table 7). The greater wheat NUEy after sunflower in 2007 was due to a lower wheat nitrogen uptake (NU) and similar grain yields when compared to pea. The lower wheat NU after sunflower in 2007 was related to the very low amount of mineral N available in soil (0-120 cm depth) before wheat sowing: 11 kg N ha^{-1} compared to 43 kg N ha^{-1} and 59 kg N ha^{-1} with winter and spring peas as preceding crops, respectively.

The use of cover crops significantly influenced wheat WUE_y in 2009, with higher mean values in BF (12.8 kg ha^{-1} mm^{-1}) than in CC (10.4 kg ha^{-1} mm^{-1}) for preceding crops. Conversely, no effects were observed on wheat NUE_y when cover crops were included in the rotations. The year had a significant influence on WUE_y, with higher values in 2005 and 2007 than in other years. Similarly, NUE_y was also significantly influenced by the year, with a value in 2009 (16 kg kg^{-1}) lower than those in other years (21.1 to 22.4 kg kg^{-1}) (Table 7).

The preceding crop significantly influenced soil water and mineral N contents at several soil depths in mid-November, immediately before durum wheat sowing (Table 4). Sunflower as a preceding crop led to lower soil water content than spring pea at 60-90 cm depth and lower than winter and spring peas at 90-120 cm depth (Fig. 3b). Winter and spring peas as preceding crops led to higher soil mineral N content throughout the soil profile than did the non-legume cash crop (i.e. sunflower) (Fig. 3d). Similarly, regardless of the preceding crop, cover crops reduced the amount of mineral N in mid-November compared to those in the BF treatment at all depths except for the deepest (90-120 cm), at which no differences were observed between BF and CC when sunflower preceded wheat (data not shown).

4. Discussion

Cropping system experiments are designed to reflect a coherent management strategy and, as a consequence, commonly differ by more than one factor (Drinkwater et al. 2000). Accordingly, besides the crop sequence, several other management practices were adapted to reach a favorable system performance based on decision rules, as demonstrated by Debaeke et al. (2009).

4.1. Adaptating cropping systems to include grain legumes in durum wheat production

The lower amounts of N fertilizers applied to legume-based rotations represent significant savings of N fertilizer for farmers. While the effect on N fertilizer applied is positive for the environment, the effect on WUE is negative. It is well known that the carbon cost of producing one gram of legume grain is higher than that of cereals (Munier-Jolain and Salon, 2005). This could partly explain the higher water use efficiency in producing biomass and grain C in the cropping systems without grain legumes (GL0-BF and GL0-CC). In the GL2-BF and GL2-CC cropping systems, insertion of soybean in the rotation was accompanied by increased irrigation needs due to the high evapotranspirative demand of this crop (Karam et al. 2005). However, both $WUE_{b\text{-}C}$ and $WUE_{y\text{-}C}$ in the GL2-BF and GL2-CC systems with spring pea and soybean were similar to those for winter pea (GL1-BF and GL1-CC). The rotation cycle significantly influenced the water use efficiencies for biomass and yield C, with higher values in 2005-2007 than 2008-2010. This result was due to more rain falling in 2008-2010, which increased the amount of water available to the crops, lowering the WUE of the cropping systems.

The insertion of one (winter peas) and two (spring pea and soybean) grain legumes in the cropping systems without cover crops (GL1-BF and GL2-BF) reduced durum wheat N fertilization by 28% and 30%, respectively, confirming the well-known positive role of biological N fixation in reducing N fertilizer requirements (Voisin et al. 2014). However, depending on pedoclimatic conditions, grain legumes can lead to greater accumulation of mineral N in the soil, as observed in our study (Fig. 3d). This accumulation increases the risk of N losses to subsurface water as nitrate leaching, which can be exacerbated by the usually lower root-length density of grain legumes than cereal crops (Hamblin and Tennant, 1987). Thus, when the objectives are to maintain yield and reduce environmental impacts, grain-legume-based cropping systems must be accompanied by cover crops to effectively reduce nitrate leaching into the groundwater (Plaza-Bonilla et al. 2015). However, according to our findings that inclusion imples a lower reduction of N fertilization, from 28-30% to 8-18%.

4.2. *Adaptating cropping systems to insert cover crops for durum wheat production*

Insertion of cover crops in the rotations was accompanied by a 36, 52 and 29 mm yr^{-1} increase in irrigation in GL0-CC, GL1-CC and GL2-CC, respectively, compared to their counterparts without cover crops. However, including cover crops did not reduce the rotation water use efficiency in producing biomass and grain C in the cropping systems. Irrigation helped ensure adequate establishment of the cover crops sown during August and September, usually under low soil water contents, a practice not expected to be performed by most farmers. The low rate of irrigation and early date of cover crop termination reduced preemptive competition for water with the subsequent cash crop, as shown by the lack of differences in wheat yields with or without cover crops. However, systems without cover crops had higher wheat WUE_y than those with them, a difference that was particularly significant in 2009, the year with the highest rainfall. Management practices must be adapted to avoid adverse effects of cover crops on the water requirements of subsequent cash crops (Dabney et al. 2001; Alonso-Ayuso et al. 2014).

Insertion of cover crops leaded to a lower saving of N fertilization of wheat in comparison to BF either with one or two grain legumes in the rotation. This result illustrates the pre-emptive competition effect induced for N by cover crops under certain conditions and in particular with low drainage during winter (Thorup-Kristensen and Nielsen, 1998). Given the unusual dry conditions during four years of the 6-year experiment, the benefits of cover crops for nitrate leaching reduction were scarce (Plaza-Bonilla et al. 2015). As a consequence, mineral N availability was lower in the systems with CC compared to BF due to N uptake of CC and a low nitrate-N leaching, leading to greater preemptive N competition. In order to maintain similar yields than in BF, N fertilizer rate was increased in CC as a logical result of the use of the balance-sheet method for adapting N fertilization. This result is another example of the need to adapt N fertilization each year according to climatic conditions and the preceding cash crop and the presence of cover crops. The lack of differences in wheat yield, protein concentration and 1000-grain weight between BF and CC demonstrates that the N fertilization was very well adapted each year thanks to the use of balance-sheet method, which allows producing relevant practical recommendations for farmers in order to adapt their N fertilization by field and by year.

Averaging the six growing seasons, wheat NUE_y did not differ between cover-crop treatments (BF and CC). However, with winter pea and spring pea as preceding crops in 2006 and 2008, the use of mustard as a cover crop reduced wheat's NUE_y. The increase in wheat N fertilization in GL1-CC and GL2-CC compared to their counterparts without cover crops (GL1-BF and GL2-BF) could partly explain these findings. Alternately, mustard produced more biomass in 2006 and 2009 than in other years (i.e. 2.2 and 3.6 t ha^{-1}, respectively), which could have increased preemptive competition for N with the subsequent wheat crop. Contrary to our findings, Dabney et al. (2001) demonstrated that cover crops can increase nutrient use efficiency of cropping systems. Similarly, in a simulation study with the NLEAP model, Delgado (1998) predicted higher N use efficiency when using cover crops compared to bare fallow in a lettuce/winter cover crop/potato rotation in Colorado, USA. However, in a recent meta-analysis, Quemada et al. (2013) found conflicting responses of NUE_y depending on the type of cover crop. While NUE_y after legume cover crops was slightly higher than that after bare fallow, it was the same or slightly lower after non-legume cover crops. Our results agree with Quemada et al. (2013); however, as they indicated, more data are needed to confidently establish the influence of cover crops on NUE. To avoid this preemptive competition for N, one effective solution is to grow a mixture of species including legumes as a cover crop. For instance, Tribouillois et al. (2015) showed that some cover crop mixtures (e.g. vetch and turnip) simultaneously reduce nitrate leaching and serve as green manure for the subsequent cash crop.

Results show that carefully designed cropping system incorporating grain legumes and cover crops produce cereal yields similar to those in traditional systems with a lower amount of N fertilizer. However, profitability is of importance for farmers to adopt these new cropping systems. Introducing a CC entails extra costs with respect to the fallow (e.g. seeds, extra field operations related to weed and soil management, etc.) (Gabriel et al. 2013). Preliminary data from the same experiment showed an average reduction of 30% in semi-net margin (Loyce et al. 2002) in the cropping systems including cover crops (Nogué-Serra, 2015).

4.3. Selecting an adequate preceding crop for durum wheat

Averaging the six growing seasons, no differences were observed in wheat WUE_y among preceding crops. However, the use of sunflower led to lower soil water content at the deepest soil layers. The ability of sunflower to extract more water from deep soil layers than other crops has been observed in several studies (Connor and Sadras, 1992; Dardanelli et al. 1997) and is an aspect that farmers consider when selecting the subsequent crop in dry climates. The adequate amount of water available (i.e. rainfall and soil water content at sowing) during the durum wheat growing season (i.e. November-May) could explain the lack of significant differences in its WUE_y among preceding crops.

The preceding crops studied had no significant influence on wheat yield or N use efficiency, although a trend for higher yield was observed when winter pea preceded durum wheat. Using legumes as preceding crops usually increases subsequent cereal yields and N uptake and reduces economic-optimum N rates (e.g. Soon et al. 2001; Gan et al. 2003; St. Luce et al. 2015). In a recent study, Angus et al. (2015) reviewed the influence of many break crops on subsequent wheat yields. They reported an increase in wheat grain of 0.63 t ha^{-1} when following grain legumes compared to wheat following wheat. The lack of continuous wheat cropping in our experiment could explain the lower yield increase observed when wheat was grown after spring and winter peas compared to sunflower (0.18 and 0.38 t ha^{-1}, respectively).

Our experiment indicated that legume cultivation saved up to 40-49 kg N ha^{-1} in durum wheat. However, using winter pea as a preceding crop only slightly increased wheat grain weight (by 1 g per 1000 grains) compared to using sunflower and did not influence grain protein concentration. Two reasons could explain this finding: (i) N fertilization was adapted to the N availability in each cropping system, and (ii) none of the crops preceding durum wheat was a cereal. Gan et al. (2003) reported a 6% and 11% increase in durum wheat grain protein concentration after oilseeds and pulses, respectively, compared to that after spring wheat (*Triticum aestivum L*.). Similar to our results, Badaruddin and Meyer (1994) found a 21% increase in wheat NUE_y when following legumes compared to continuous wheat monocropping. Besides the positive effect of symbiotic fixation of N_2 by legumes, crop rotation effects, such as breaking pest and disease cycles and reducing weed pressure, have a synergistic influence that can increase yields of subsequent crops.

5. Conclusions

The results of this experiment show that through careful design and consideration of well-known agronomic rules, cropping systems that incorporate grain legumes and cover crops strongly decrease N fertilizer rates (by 13-30% for wheat and 49-61% at the rotation level) without decreasing wheat yield or grain quality significantly. Nevertheless, production of biomass and grain C in the rotation had lower water use efficiency when grain legumes were inserted. Our results also indicate that inserting cover crops must be accompanied by a careful redesign of the cropping system to compensate for the possible consequences of preemptive competition for N and water.

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Figure captions

Fig. 1 Conceptual diagram of the cropping systems compared. GL0, GL1 and GL2 correspond to three-year rotations with 0, 1 and 2 grain legumes, respectively. Cash crops are shown in bold. Arrows represent the period between cash crops, under bare fallow (BF) in the GL0-BF, GL1-BF and GL2-BF cropping systems. Cover crops (CC) used in the GL0-CC, GL1-CC and GL2-CC cropping systems are shown inside the arrows and in italics.

Fig. 2 Daily (a) air temperature and (b) cumulative rainfall from July to June during the six cropping seasons of the experiment.

Fig. 3 Soil water (mm) and mineral N (kg N ha^{-1}) contents in mid-November affected by cropping system (a and c, respectively) and durum wheat preceding crop (b and d, respectively). GL0, GL1 and GL2 correspond to 3-year rotations with 0, 1 and 2 grain legumes, respectively; BF and CC stand for “bare fallow” and “cover crops”, respectively. Values are means from 2005-2010. ANOVA results are shown in Table 4. For a given soil depth, different lower-case letters indicate significant differences between treatments at P<0.05.

Table 1. N fertilizer rates applied to cash crops of the cropping systems compared (GL0, GL1 and GL2 correspond to 3-year rotations with 0, 1 and 2 grain legumes, respectively; BF and CC stand for "bare fallow" and "cover crops", respectively) during the experimental period (2005-2010). Note that legume cash crops or cover crops did not received any N fertilizer.

Cropping system	Cash crop	N fertilization rate (kg N ha^{-1})							
		Year							3-yr N applied (entire rotation)
		2005	2006	2007	2008	2009	2010	Mean	
GL0-BF	Sorghum	76	76	82	83	112	60	82	303
	Sunflower	56	51	51	62	67	40	55	
	Durum wheat	132+50	99+50	100+54	101+57	42+74+55	100+80	166	
GL0-CC	Sorghum	76	76	82	83	112	60	82	295
	Sunflower	56	51	51	62	67	40	55	
	Durum wheat	88+50	99+50	100+54	101+57	42+74+55	100+80	158	
GL1-BF	Sunflower	0	0	0	0	34	0	6	126
	Durum wheat	66+50	50+50	50+54	40+57	106+55	60+80	120	
GL1-CC	Sunflower	0	0	0	0	34	0	6	151
	Durum wheat	66+50	99+50	100+54	70+57	106+55	80+80	145	
GL2-BF	Durum wheat	88+50	50+50	50+54	40+57	42+37+55	80+50	117	117
GL2-CC	Durum wheat	88+50	99+50	50+54	70+57	42+56+55	60+50	130	130

Table 2. Irrigation rates (mm) applied to crops depending on cropping system (GL0, GL1 and GL2 correspond to 3-year rotations with 0, 1 and 2 grain legumes, respectively; BF and CC stand for “bare fallow” and “cover crops”, respectively) during the experimental period (from cash-crop harvest in 2004 to cash-crop harvest in 2010). Values for cover crops are shown in italics. Note that the cash crops in the BF and CC cropping systems received the same amount of irrigation water.

Cropping system	Cash crop *Cover crop*	Irrigation rate (mm)							
		Year							
		2004	2005	2006	2007	2008	2009	2010	Mean
GL0-BF GL0-CC	Sorghum	-	103	94	48	77	85	73	80
	Bare fallow	*0*	*0*	*0*	*0*	*0*	*0*	-	*0*
	Sunflower	-	72	46	0	0	0	0	20
	Vetch	*0*	*0*	*0*	*0*	*45*	*58*	-	*17*
	Durum wheat	-	0	0	0	0	23	0	4
	Vetch-Oat	*20*	*30*	*30*	*0*	*0*	*34*	-	*19*
GL1-BF GL1-CC	Sunflower	-	48	0	0	0	0	0	8
	Mustard	*20*	*0*	*27*	*0*	*0*	*53*	-	*17*
	Winter pea	-	0	0	0	0	0	0	0
	Mustard	*20*	*0*	*25*	*0*	*0*	*50*	-	*16*
	Durum wheat	-	0	0	0	0	22	0	4
	Vetch-Oat	*20*	*28*	*30*	*0*	*0*	*34*	-	*19*
GL2-BF GL2-CC	Soybean	-	180	185	141	132	128	0	128
	Bare fallow	0	0	0	0	0	0	-	0
	Spring pea	-	30	41	0	0	0	0	12
	Mustard	*20*	*0*	*25*	*0*	*0*	*50*	-	*16*
	Durum wheat	-	0	0	0	0	77	0	13
	Mustard	*25*	*28*	*0*	*0*	*0*	*24*	-	*13*

Table 3. Cumulative water drainage predicted by STICS and rotation water use efficiency for the production of aboveground biomass C ($WUE_{b\text{-}C}$) and grain C ($WUE_{y\text{-}C}$) as affected by the cropping systems compared (GL0, GL1 and GL2 correspond to 3-year rotations with 0, 1 and 2 grain legumes, respectively; BF and CC stand for "bare fallow" and "cover crops", respectively) for each of the two rotation cycles (2005-2007 and 2008-2010). Values in parentheses correspond to the standard deviation.

Cropping system	Predicted cumulative drainage (mm)			$WUE_{b\text{-}C}$ (kg C ha^{-1} mm^{-1})			$WUE_{y\text{-}C}$ (kg C ha^{-1} mm^{-1})		
	Rotation cycle			Rotation cycle			Rotation cycle		
	2005-2007	2008-2010	2005-2010 sum	2005-2007	2008-2010	2005-2010 mean	2005-2007	2008-2010	2005-2010 mean
GL0-BF	132 (36)	464 (29)	596 (65) ab*	0.92 (0.07)	0.86 (0.10)	0.89 (0.09) a	4.19 (0.27)	3.91 (0.36)	4.05 (0.34) a
GL0-CC	111 (52)	483 (40)	594 (69) ab	0.89 (0.09)	0.87 (0.10)	0.88 (0.09) ab	3.99 (0.21)	3.97 (0.35)	3.98 (0.28) a
GL1-BF	111 (43)	423 (71)	534 (113) b	0.83 (0.12)	0.72 (0.04)	0.78 (0.11) bc	3.53 (0.66)	2.81 (0.14)	3.17 (0.59) b
GL1-CC	114 (6)	381 (44)	495 (50) b	0.78 (0.10)	0.70 (0.05)	0.74 (0.08) cd	3.27 (0.51)	2.77 (0.11)	3.02 (0.44) b
GL2-BF	172 (37)	563 (63)	735 (100) a	0.75 (0.09)	0.73 (0.07)	0.74 (0.08) cd	3.49 (0.28)	3.16 (0.36)	3.33 (0.35) b
GL2-CC	91 (18)	440 (114)	531 (128) b	0.70 (0.05)	0.64 (0.06)	0.67 (0.06) d	3.30 (0.25)	2.67 (0.31)	2.99 (0.43) b
Mean	122 (42) B¶	459 (84) A	581 (116)	0.81 (0.11) A	0.75 (0.11) B	0.78 (0.12)	3.63 (0.51) A	3.21 (0.60) B	3.42 (0.59)
Kruskal-Wallis test									
Cropping system		*0.290*			*<0.001*			*<0.001*	
Rotation cycle		*<0.001*			*0.021*			*0.004*	

*For a given variable, different lower-case letters indicate significant differences between cropping systems at $P<0.05$. ¶ For a given variable, different upper-case letters indicate significant differences between rotation cycles at $P<0.05$.

Table 4. Results of analysis of variance for soil water and soil mineral nitrogen contents measured in mid-November as affected by cropping system and the crop preceding durum wheat for the 2005-2010 period. Log-transformation was used to normalize mineral N data.

	Effects	Soil water content (SWC) in mid-November	Soil mineral nitrogen content (SMN) in mid-November
Comparison of cropping systems	*Cropping system (CS)*	*< 0.001*	*< 0.001*
	Year (Y)	*< 0.001*	*< 0.001*
	CS x Y	*0.655*	*0.003*
	Depth (D)	*< 0.001*	*< 0.001*
	D x Y	*< 0.001*	*< 0.001*
	CS x D	*0.085*	*0.005*
	CS x D x Y	*1.0*	*0.99*
Comparison of crop preceding wheat	*Preceding crop (PreC)*	*0.131*	*0.066*
	Year (Y)	*< 0.001*	*< 0.001*
	Cover-crop treatment (CCt)	*0.038*	*< 0.001*
	Depth (D)	*< 0.001*	*< 0.001*
	PreC x Y	*0.006*	*< 0.001*
	PreC x CCt	*0.202*	*0.005*
	PreC x D	*0.003*	*0.042*
	CCt x D	*0.444*	*< 0.001*
	CCt x Y	*0.101*	*0.707*
	D x Y	*0.014*	*< 0.001*
	PreC x CCt x Y	*0.964*	*0.006*
	CCt x Y x D	*0.474*	*0.378*
	PreC x CCt x D	*0.732*	*0.006*
	PreC x Y x D	*0.726*	*0.097*
	PreC x CCt x Y x D	*0.998*	*0.565*

Table 5. Durum wheat N uptake, apparent N recovery efficiency (NAR) and N harvest index (NHI) as affected by the preceding crop (sunflower, winter pea and spring pea - *PreC*), cover-crop treatment (BF is bare fallow; CC is cover crop) and year. Values are means from 2005-2010. Values between parentheses correspond to the standard deviation.

Effects	Durum wheat indicators of performance		
	N uptake (kg N ha^{-1})	NAR (%)	NHI
Sunflower *PreC*	197 (39)	71 (19)	0.60 (0.06)
Winter pea *PreC*	216 (42)	75 (25)	0.59 (0.05)
Spring pea *PreC*	208 (55)	76 (21)	0.60 (0.07)
Bare fallow (BF)	211 (45)	75 (20)	0.60 (0.06)
Cover crop (CC)	203 (47)	73 (23)	0.60 (0.05)
Sunflower *PreC*-BF	198 (40)	70 (17)	0.60 (0.06)
Winter pea *PreC* -BF	220 (42)	79 (27)	0.59 (0.05)
Spring pea *PreC* -BF	215 (52)	75 (16)	0.60 (0.07)
Sunflower *PreC* -CC	197 (40)	71 (21)	0.61 (0.05)
Winter pea *PreC* -CC	212 (43)	71 (24)	0.59 (0.04)
Spring pea *PreC* -CC	201 (60)	76 (26)	0.60 (0.06)
		ANOVA	
Preceding crop (PreC)	*0.063*	*0.146*	*0.452*
Cover crop treatment (CCt)	*0.08*	*0.303*	*0.502*
PreC x CCt	*0.311*	*0.256*	*0.664*
Year (Y)	*< 0.001*	*< 0.001*	*< 0.001*
PreC x Y	*0.099*	*0.294*	*0.036*
CCt x Y	*0.573*	*0.181*	*0.781*
PreC x CCt x Y	*0.205*	*0.087*	*0.870*

Table 6. Durum wheat grain yield and grain quality parameters affected by preceding crop and cover-crop treatments during the experimental period (2005-2010). GL0, GL1 and GL2 correspond to 3-year rotations with 0, 1 and 2 grain legumes, respectively. Values are the mean of the BF (bare fallow) and CC (cover crop) treatments. Values in parentheses correspond to standard deviations.

Preceding crop	Cropping system	Durum wheat yield C and N components						
		2005	2006	2007	2008	2009	2010	Mean
				Durum wheat grain yield (kg ha^{-1})				
Sunflower	GL0	5310 (317)	4375 (980)	5783 (348)	4894 (453)	4116 (567)	5481 (406)	4993 (783)
Winter pea	GL1	5236 (214)	5609 (683)	6015 (375)	5348 (157)	4044 (538)	6010 (382)	5377 (780)
Spring pea	GL2	5054 (512)	4823 (620)	5622 (192)	5509 (236)	3687 (1068)	6125 (353)	5137 (938)
Mean		5200 (352) B ¶	4936 (882) B	5807 (331) A	5250 (390) B	3949 (718) C	5872 (452) A	5169 (840)
				Durum wheat 1000-grain weight (g)				
Sunflower	GL0	46.6 (2.4) a*	42.7 (1.1)	38.3 (1.3)	35.2 (1.9)	39.6 (3.1) c	45.8 (1.0)	41.4 (4.5) b
Winter pea	GL1	43.4 (3.1) b	43.9 (1.0)	36.7 (1.9)	36.2 (2.7)	48.3 (0.9) a	45.8 (0.8)	42.3 (4.9) a
Spring pea	GL2	42.7 (3.2) b	44.3 (2.2)	37.8 (1.0)	37.7 (1.4)	42.5 (1.0) b	45.0 (1.2)	41.7 (3.4) b
Mean		44.2 (3.2) AB	43.6 (1.6) B	37.6 (1.5) C	36.3 (2.2) C	43.4 (4.2) B	45.5 (1.0) A	41.8 (4.3)
				Durum wheat grain N content (kg N ha^{-1})				
Sunflower	GL0	121 (10)	102 (25) b	132 (9)	114 (12)	108 (13)	131 (13)	118 (17)
Winter pea	GL1	118 (15)	138 (17) a	142 (15)	121 (9)	100 (17)	142 (9)	127 (20)
Spring pea	GL2	119 (8)	112 (13) b	143 (7)	123 (9)	93 (25)	143 (11)	122 (22)
Mean		119 (10) B	117 (24) B	139 (11) A	119 (10) B	100 (18) C	139 (11) A	122 (20)
				Durum wheat grain protein concentration (g 100 g^{-1})				
Sunflower	GL0	12.9 (0.4)	13.2 (0.4)	13.0 (0.8) b	13.3 (0.3)	15.0 (0.8) a	13.6 (0.6)	13.5 (0.9)
Winter pea	GL1	12.8 (1.1)	14.1 (0.3)	13.5 (0.6) b	12.9 (0.6)	14.0 (0.8) b	13.5 (0.3)	13.5 (0.8)
Spring pea	GL2	13.4 (0.7)	13.3 (0.5)	14.5 (0.7) a	12.7 (0.5)	14.4 (0.5) ab	13.3 (0.7)	13.6 (0.9)
Mean		13.0 (0.8) CD	13.5 (0.6) BC	13.6 (0.9) B	12.9 (0.5) D	14.5 (0.8) A	13.5 (0.5) BC	13.3 (0.8)

ANOVA

	Grain yield	1000-grain weight	Grain N content	Protein conc.
Preceding crop (PreC)	*0.355*	*0.014*	*0.202*	*0.75*
Cover-crop treatment (CCt)	*0.058*	*0.057*	*0.013*	*0.625*
Year (Y)	*< 0.001*	*< 0.001*	*< 0.001*	*< 0.001*
PreC x CCt	*0.112*	*0.272*	*0.023*	*0.572*
PreC x Y	*0.125*	*< 0.001*	*0.062*	*0.019*
CCt x Y	*0.273*	*0.365*	*0.205*	*0.219*
PreC x CCt x Y	*0.152*	*0.767*	*0.049*	*0.278*

*For a given year, different lower-case letters indicate significant differences between preceding crops at $P<0.05$. ¶ Different upper-case letters indicate significant differences between years at $P<0.05$.

Table 7. Effect of the preceding crop and cover-crop treatments (BF is bare fallow; CC is cover crop) on durum wheat water and nitrogen use efficiencies for yield (WUE$_y$ and NUE$_y$, respectively) during the experimental period (2005-2010). Values in parentheses correspond to standard deviations.

Preceding crop	Cover crop	Year 2005	2006	2007	2008	2009	2010	Mean	ANOVA	
					Durum wheat WUE$_y$ (kg ha^{-1} mm^{-1})					
	BF	14.2 (0.9)	10.8 (3.8)	15.0 (0.5)	10.5 (0.5)	15.6 (4.0)	12.3 (1.7)	13.1 (2.7)		
Sunflower	CC	15.1 (0.8)	9.5 (1.2)	15.5 (1.3)	12.2 (0.6)	11.7 (1.1)	12.0 (0.7)	12.7 (2.3)		
	Mean	14.7 (0.9)	10.1 (2.4) b*	15.3 (0.9)	11.4 (1.1)	13.7 (3.3)	12.2 (1.1)	12.9 (2.5)		
	BF	14.8 (1.9)	15.2 (0.1)	13.6 (0.9)	13.0 (0.2)	9.3 (1.4)	13.0 (1.1)	13.2 (2.2)	*Preceding crop (PreC)*	*0.909*
Winter pea	CC	13.7 (0.0)	13.3 (0.1)	15.6 (1.3)	11.8 (0.5)	10.6 (0.6)	12.3 (0.6)	12.9 (1.7)	*Cover crop (CCt)*	*0.014*
	Mean	14.3 (1.2)	14.3 (1.1) a	14.6 (1.5)	12.4 (0.8)	10.0 (1.2)	12.6 (0.8)	13.0 (1.9)	*Year (Y)*	*< 0.001*
	BF	14.5 (1.6)	12.1 (1.8)	13.0 (0.5)	13.9 (0.0)	13.7 (0.5)	12.3 (0.9)	13.3 (1.2)	*PreC x CCt*	*0.095*
Spring pea	CC	13.7 (1.8)	11.0 (0.7)	14.6 (1.2)	12.1 (0.4)	8.9 (2.8)	12.0 (1.5)	12.1 (2.3)	*PreC x Y*	*0.001*
	Mean	14.1 (1.5)	11.5 (1.3) ab	13.8 (1.2)	13.0 (1.1)	11.3 (3.2)	12.1 (1.0)	12.7 (1.9)	*CCt x Y*	*0.041*
Rotation mean		14.4 (1.1) A¶	12.0 (2.4) B	14.6 (1.2) A	12.3 (1.1) B	11.6 (2.9) B	12.3 (0.9) B	12.9 (2.1)	*PreC x CCt x Y*	*0.140*
					Durum wheat NUE$_y$ (kg kg^{-1})					
	BF	20.0 (0.0)	19.1 (3.8)	23.0 (2.8)	19.5 (1.1)	17.7 (2.1)	21.0 (0.6)	20.1 (2.4)		
Sunflower	CC	20.5 (0.3)	20.9 (1.8)	24.0 (1.2)	21.3 (0.6)	15.2 (1.8)	20.7 (0.0)	20.4 (2.9)		
	Mean	20.3 (0.3)	20.0 (2.6) b	23.5 (1.8) a	20.4 (1.3) b	16.4 (2.2)	20.8 (0.4)	20.2 (2.6)		
	BF	23.6 (0.9)	26.3 (0.4)	21.3 (1.1)	24.3 (0.2)	13.9 (0.9)	23.2 (2.2)	22.1 (4.2)	*Preceding crop (PreC)*	*0.243*
Winter pea	CC	22.4 (0.3)	20.4 (1.1)	22.0 (1.1)	22.6 (0.7)	16.1 (2.5)	22.6 (2.1)	21.0 (2.7)	*Cover crop (CCt)*	*0.113*
	Mean	23.0 (0.9)	23.4 (3.5) a	21.6 (1.0) ab	23.4 (1.0) a	15.0 (2.0)	22.9 (1.8)	21.6 (3.5)	*Year (Y)*	*< 0.001*
	BF	22.2 (2.8)	25.7 (2.5)	19.7 (0.1)	22.5 (0.6)	19.9 (3.0)	21.0 (1.9)	21.8 (4.5)	*PreC x CCt*	*0.121*
Spring pea	CC	22.8 (3.0)	22.2 (3.8)	19.6 (1.7)	24.3 (3.1)	13.4 (3.6)	24.6 (1.6)	21.2 (4.5)	*PreC x Y*	*0.016*
	Mean	22.5 (2.4)	23.9 (3.3) a	19.7 (1.0) b	23.4 (2.1) a	16.7 (4.6)	22.8 (2.5)	21.5 (3.6)	*CCt x Y*	*0.109*
Rotation mean		21.9 (1.8) A	22.4 (3.4) A	21.6 (2.0) A	22.4 (2.0) A	16.0 (3.0) B	22.2 (1.9) A	21.1 (3.3)	*PreC x CCt x Y*	*0.043*

*For a given year, different lower-case letters indicate significant differences between preceding crops at *P*<0.05. ¶ Different upper-case letters indicate significant differences between years at *P*<0.05.

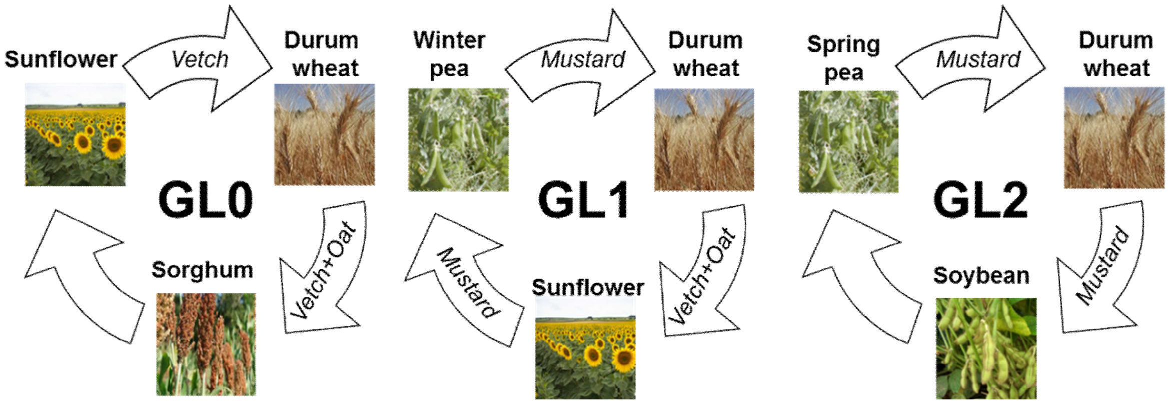

GL0
Sunflower
Vetch
Durum wheat
Vetch+Oat
Sorghum
GL1
Winter pea
Mustard
Durum wheat
Vetch+Oat
Sunflower
Mustard
GL2
Spring pea
Mustard
Durum wheat
Mustard
Soybean

Figure 1

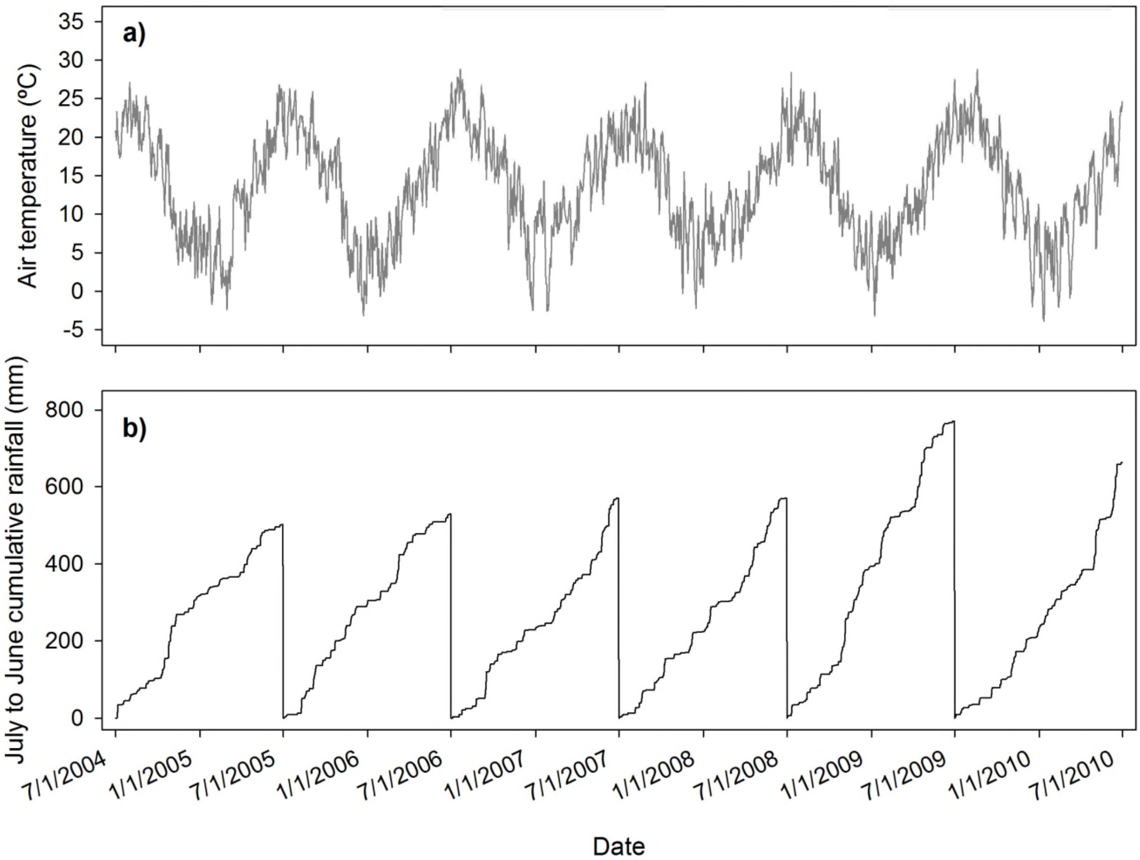
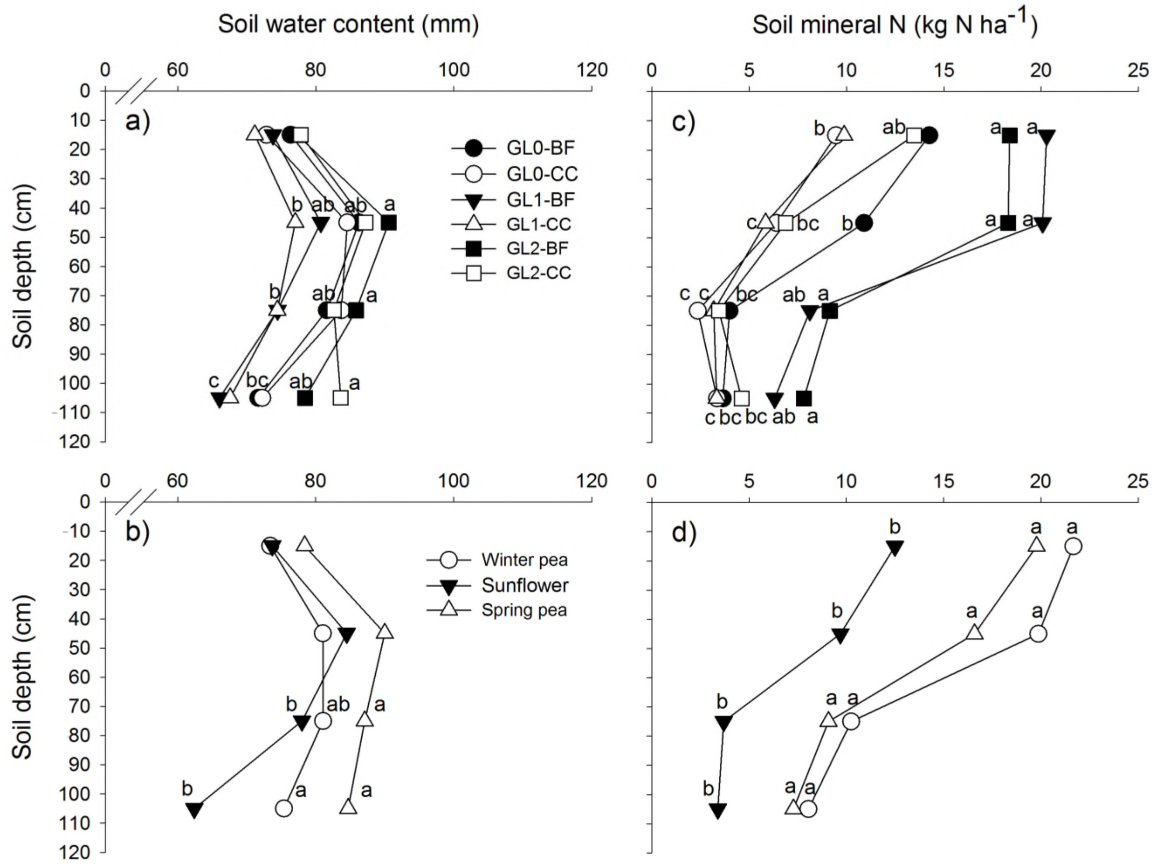

a)
Air temperature (ºC)
35
30
25
20
15
10
5
0
-5
b)
July to June cumulative rainfall (mm)
800
600
400
200
0
7/1/2004
1/1/2005
7/1/2005
1/1/2006
7/1/2006
1/1/2007
7/1/2007
1/1/2008
7/1/2008
1/1/2009
7/1/2009
1/1/2010
7/1/2010
Date

Figure 2

687



688 **Figure 3**